

Influence of soil water content on filter cake formation during drilling fluid injection

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ABSTRACT: Bentonite support fluid plays a crucial role in the temporary stabilization of excavation walls during the construction of deep foundations or underground structures, primarily through the formation of a filter cake that limits fluid loss and transfers lateral pressure to the surrounding soil. While the effects of fluid properties and soil permeability have been widely studied, the impact of the initial water content of the host soil remains underreported. Thus, the results of a preliminary experimental study concerning the effects of soil water content on bentonite fluid filtration are presented here. Tests were conducted in a laboratory cell filled with sand in which a bentonite fluid was injected under a constant pressure of 100 kPa. Two initial water contents were tested: 2% and 8%, corresponding to degrees of saturation of 6% and 26%, respectively. Results revealed a three-phase filtration process: rapid infiltration, clogging and internal cake formation, and progressive filtration (external cake formation and thickening). At a water content of 2%, no filtrate was collected, indicating immediate pore clogging. At a water content of 8%, more than 3.2 L of filtrate was recovered. At the end of the bentonite injection, the final water content profiles in the soil (sand + retained bentonite fluid) were more uniform for an initial water content of 2% than for 8%. Bentonite retention was uniform throughout the sand depth at 2%, while at 8%, the retention was greater across the soil depth. The filter cake was thicker in the water content of 2% than that 8%. These results demonstrate that the initial water content of the studied soil influences filtration behavior and cake formation. Ongoing studies aim to further quantify this effect and support field practices adapted to site-specific moisture conditions.

KEYWORDS: Bentonite fluid, filter cake, soil water content, hydraulic conductivity, filtration mechanisms.

1 INTRODUCTION

Bentonite fluid has been used to temporarily support civil engineering excavations. This thixotropic clay suspension forms an internal and/or external impermeable filter layer on trench walls that transfers hydrostatic pressure to the surrounding soil and prevents cave-ins (Comodromos et al., 2013; Vipulanandan et al., 2020; Qin et al., 2023a). This technique enables the construction of deep foundations and underground structures below the water table, while minimizing ground movements (Xu et al., 2019; Yin et al., 2021; Jin et al., 2023).

Inadequate fluid control can compromise excavation stability and is reported to influence defects, occurrence such as shadowing – the imprint of reinforcement cages in hardened concrete (Kmeid et al., 2023) – or the inclusion of bentonite fluid, observed at panel joints. Chemical contamination of bentonite by ions (Ca^{2+} , Mg^{2+} , sulfates) or acidic pH can affect the fluid rheological profile and lead to a more permeable filter cake, destabilizing the excavation (Choo et al., 2015; Min et al., 2019; Choo et al., 2020; Abed et al., 2024; Wang et al., 2025). Filtrate flow into the soil first creates an internal cake by pore clogging, then an external cake at the surface – a quasi-impermeable layer limiting fluid loss and ensuring trench wall stability (Nguyen et al., 2012; Lee et al., 2016; Xu et al., 2019; Min et al., 2019; Qin et al., 2023b). Optimal cake thickness is critical: if too thin, it leads to instability and fluid losses (Dong et al., 2024; Zhang et al., 2025); if too thick, it may affect fresh concrete flow, causing shadowing (Kmeid et al., 2023).

Filter cake quality (thickness, permeability, continuity) depends on several factors. Drilling conditions (overpressure, flow rate) influence filtration dynamics: higher pressure increases fluid penetration and cake growth (Ramadan et al., 2024). The physicochemical properties of the fluid – bentonite type and concentration – also play a role: higher clay content leads to thicker, less permeable cakes (Benna et al., 2001; Wang et al., 2021). Electrolytes and contaminants (e.g., salt water) inhibit bentonite swelling and increase cake porosity (Qin et al., 2023c; Zhang et al., 2024). Weighting agents (barite, hematite, ilmenite) affect grain size and cake thickness (Bageri et al., 2021), while soil hydraulic properties (permeability, porosity) govern filtrate flow and cake formation (Lin et al., 2022; Qin et al., 2023). However, in-situ uncertainties remain due to complex couplings (fluid-structure interaction, subsurface moisture), which make prediction difficult.

A key parameter remains insufficiently studied: the initial water content of soils. While fluid formulation can be adjusted on-site, initial soil moisture is a fixed geological constraint that likely influences filtrate initiation, pore clogging, and cake structuring. This study seeks to isolate the effect of soil water content on bentonite fluid filtration. Founded by FNTP (National Federation of Public Works (France)) and the Normandy Region, this preliminary investigation aims to improve understanding of bentonite support systems in unsaturated or partially saturated soils.

2 MATERIALS AND METHODS

2.1 Materials

2.1.1 Soil

The soil used is a sand with a grain size range of (160-1000) μm , a median diameter (d_{50}) of 600 μm , a dry density of 1.45 g/cm^3 , and a specific unit weight of solid particles of 2.58 g/cm^3 . Its hydraulic conductivity was experimentally measured by means of a constant-head test and found to be $(3.5 \pm 0.3) \times 10^{-4}$ m/s, with a porosity of 40%.

Two water contents were tested: 2% and 8%, corresponding respectively to degrees of saturation of 6% and 26%. Notice that the water content at full saturation of the used sand is 30%.

2.1.2 Support fluid

The bentonite used is a sodium bentonite of type CM10t (Clariant (Le Treport, France)). prepared at a concentration of 45 g/L using moderately hard to hard water (an average hardness of 26 $^\circ\text{F}$ and a pH of 7). Its yield stress was 1.1 Pa, and its dynamic viscosity is 0.021 Pa.s. The pH of the prepared fluid is (9.5 ± 0.5) . Preparation was carried out at a constant temperature of (16 ± 1) $^\circ\text{C}$, resulting in a Marsh viscosity of (46 ± 2) .

2.1.3 Filtration cell

To investigate the influence of the initial water content of the soil on bentonite fluid filtration, laboratory experiments were conducted using a stainless-steel filtration cell (Figure 1) with a diameter of 29 cm and a height of 30 cm. Frontal filtration technique is used to inject the bentonite fluid across the soil under a constant injection pressure (Cf. Fig. 1).

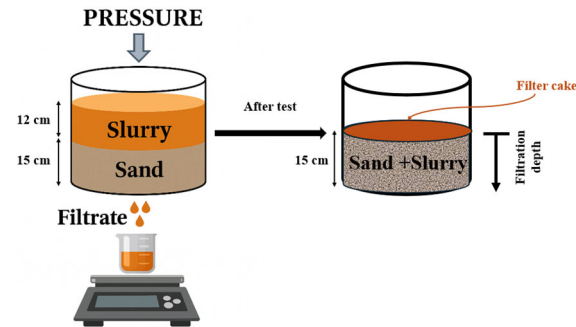


Figure 1. Schematic representation of the experimental setup

2.2 Methods

Filtration tests were conducted under controlled and identical conditions to ensure reproducibility. A constant pressure of 100 kPa was applied for 7 hours. An identical measurement protocol was used for all tests. The recorded parameters include filtrate volume as a function of time, cake thickness, water content profile, and retention(R) profile (Cf. Eq. (1)).

$$R = \frac{M_{fp}}{M_{sand}} \times 100 (\%) \quad (1)$$

With M_{fp} (g) is the mass of deposited bentonite fine particles in the sand and M_{sand} (g) is the sand mass.

Cake thickness measurements were taken at multiple locations using a Fann-standard ruler to ensure accuracy and consistency, enabling the determination of a representative average cake thickness.

Also, at the end of each test, the equivalent hydraulic conductivity of the complex (cake + fluid-impregnated sand) was derived from the change in filtrate volume over time.

3 RESULTS AND DISCUSSIONS

3.1 Filtrate volume

The experimental filtrate volume curves plotted against the square root of time (Cf. Fig. 2) show a typical three-stage filtration pattern: an initial rapid filtration phase, followed by clogging and internal cake formation, and then a progressive filtration phase (external cake formation and thickening). Figure 2 indicates that the initial water content of the soil is a critical controlling factor. After 7 hours of injection, no filtrate was collected throughout the soil in the 2% water content test, whereas at 8%, the cumulative filtrate volume exceeded 3.2 L. This pronounced difference is attributed to effective permeability in soil with 2 % water content, where strong capillary suction and high intergranular mechanical resistance greatly limit the infiltration of the fluid (Sharma, 2012). In contrast, for 8 % water content soil, pre-existing water in pores acts as a lubricant, reducing interparticle friction and enabling the bentonite fluid to penetrate more easily into the granular matrix (Sharma, 2012)

Clogging onset time, identified by the inflection point in the 8% filtrate curve, occurs approximately 2 minutes after the start of the injection test. In the 2% water content soil, however, no distinct filtration phase is initiated, suggesting that pore clogging by capillary retention (Sharma, 2012) and particle deposition occurs almost immediately, without significant fluid migration. These findings highlight the role of initial water content in controlling bentonite fluid filtration dynamics, particularly in relation to fluid mobility, and the advancement of the infiltration front.

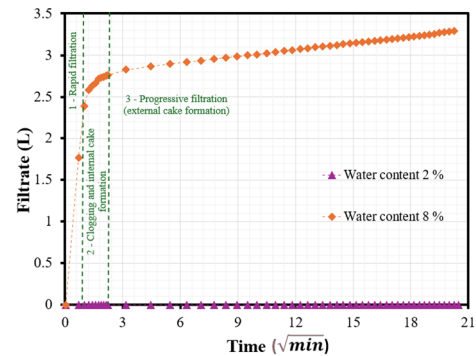


Figure 2. Filtrate volume as a function of the square root of time

3.2 Final water content and retention

The final water content profiles as a function of the soil depth after testing is presented in Figure 3. It clearly highlights the influence of the initial water content of the soil. For the soil with 2% water content, the water content reaches 31.6% for the first centimeter of the soil (0 to -1 cm) and 24% at the bottom of the cell (-14 to -15 cm). In contrast, for an initial water content of 8%, the water content decreases from 31.3% for the first centimeter of the soil (0 to -1 cm) and 22% at the bottom of the cell (-14 to -15 cm). This behavior is explained by the greater mechanical resistance of the sand at 2% water content. This resistance slows bentonite fluid flow and promotes the retention of water and fine particles at various depths (Fredlund et al., 1996). In contrast, in the soil with 8% water content, the pre-existing water acts as a lubricant, reducing friction and thus promoting faster infiltration (Berilgen et al., 2007)

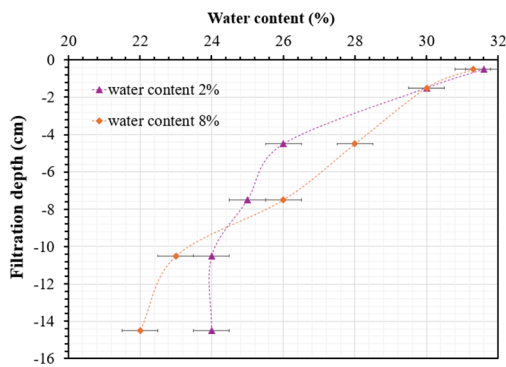


Figure 3. Final soil water-content profile, after the test

The fine particle retention profile measured at the end of the bentonite fluid injection is shown in Figure 4 for the depths ranging from -1 to -15 cm. The results indicate the influence of the soil's initial water content on the particle retention: At all depths, retention is higher in 2% water content soil than 8% water content soil. For 2% water-content soil, retention reaches 1.7% for the depths ranging between -1 and -2 cm, then decreases to 1.5% at a depth of -7 cm, reaching 1.1% at the bottom of the cell. Conversely, for a soil with an initial water content of 8%, retention reaches 1.3% at depths between -1 and -2 cm, then decreases to 1% at a depth of -7 cm, reaching to 0.8% at the bottom of the cell. As discussed before, these behaviors could be attributed to the high mechanical resistance resulting from the lack of lubrication in the 2% water-content soil, which promotes the trapping of bentonite particles throughout the infiltration path.

Regarding the first centimeter (0 to -1 cm) of soil, an average retention of 3.6 % was measured in the 2% water-content soil, whereas it was 3.3 % in the 8% water-content soil.

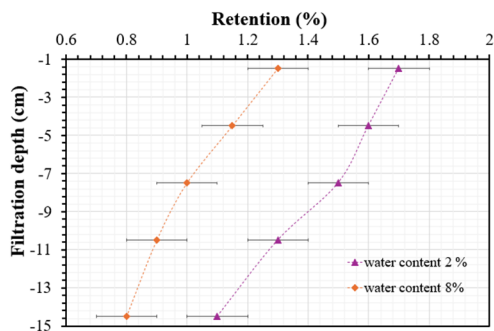


Figure 4. Retention profile of fine particles after the test

3.3 Filter cake

In Table 1 is presented the average cake thickness measured after the injection of the bentonite fluid for the two water-content studied.

Table 1. Cake thickness measured for soil at 2% and 8% water-content at the end (after 7h) of bentonite fluid injection

Water content	2%	8%
Average cake thickness (mm)	2.2	1.8

The results indicate that the initial water content affects the surface filter cake, thickness. As mentioned above, this behavior results from the previously described mechanisms: in the soil with 2% water content, mechanical resistance and capillary interfaces promote a rapid trapping of fine particles, leading to a thicker surface deposit (external cake); conversely, in 8% water content soil, this effect is reduced.

Concerning the hydraulic conductivity of the complex (clogged soil + surface filter cake (Cf. Fig. 5), at 8% water content, the

average hydraulic conductivity was 8.4×10^{-11} m/s. Notice that the initial hydraulic conductivity of the soil was 3.5×10^{-4} m/s. Thus, a complete loss of soil hydraulic conductivity is obtained. For the soil with a water content of 2%, as noted earlier, no filtrate was collected, which prevented us from determining its hydraulic conductivity. This suggests that the deposit formed in the 2% water content soil is not only thicker but also impermeable.



Figure 5. Photo of the surface cake and the internal deposition of the bentonite fluid particles

These results confirm that the initial water content of the soil governs not only the initiation of the filtration process but also the structuring and performance of the filter cake – a key parameter for maintaining lateral pressure on excavation walls during fluid-supported geotechnical works.

4 CONCLUSIONS

This preliminary study shows that the initial water content of the soil influences the filtration mechanisms. The tests carried out at 2% and 8% water content demonstrate that moisture affects bentonite fluid infiltration, fine-particle retention, and filter-cake formation.

For the soil with 2% water content, capillary suction and mechanical resistance are observed to induce rapid clogging, high particle retention, and the development of a thick filter cake that inhibits filtrate passage. Conversely, for the soil with 8% water content, the presence of water within the pores enhances fluid mobility, promoting deeper infiltration, lower retention, and the formation of a thinner external cake.

Additional experiments are currently in progress to sharpen the quantification of this phenomenon, determine a potential threshold in initial water content, and explore how it may interact with factors like applied pressure or fluid concentration.

5 ACKNOWLEDGEMENTS

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